AERATION CONTROL USING CONTINUOUS DISSOLVED OXYGEN MONITORING IN AN ACTIVATED SLUDGE WASTEWATER TREATMENT PROCESS

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ABSTRACT

The original design for the 2000 UC Davis Wastewater Treatment Plant (WWTP) relied on manual aeration control to maintain desirable dissolved oxygen (DO) levels in the oxidation ditch. Given the large daily variation in flow and wastewater strength, WWTP operators found it difficult to maintain stable DO levels. As a result, operators typically erred by providing too much oxygen, and the ditch was often found to be in an over-aerated state. Thus, the original control strategy wasted energy and promoted unstable biological conditions.

In January 2004, UC Davis installed a new system for continuously measuring DO in the oxidation ditch and automatically controlling aeration. The project scope included installing a “floating ball-type” DO monitor, adding variable speed drives (VFDs) on two aerator motors, and programming a PLC to automatically vary aeration in response to measured DO levels in the oxidation ditch.

This paper discusses the challenges of manual aeration control, the process UC Davis used to automate aeration and results for the first year of operation.

KEYWORDS

Energy Conservation, Dissolved Oxygen, Aeration Control, Oxidation Ditch

BACKGROUND

UC Davis owns and operates its own WWTP to treat wastewater generated by the campus. The current WWTP was commissioned in March of 2000. The treatment plant was designed for an average-day flow of 2.5 million gallon per day (Mgd) and a peak hourly flow of 6.3 Mgd. Wastewater treatment processes include an oxidation ditch, clarifiers, sand filter cells, and ultraviolet light disinfection. Treated effluent is discharged to the South Fork of Putah Creek. Solids handling processes for waste activated sludge include solids storage basins and solids drying beds. The dried solids are transported offsite for landfill disposal. Table 1 summarizes the treatment processes.

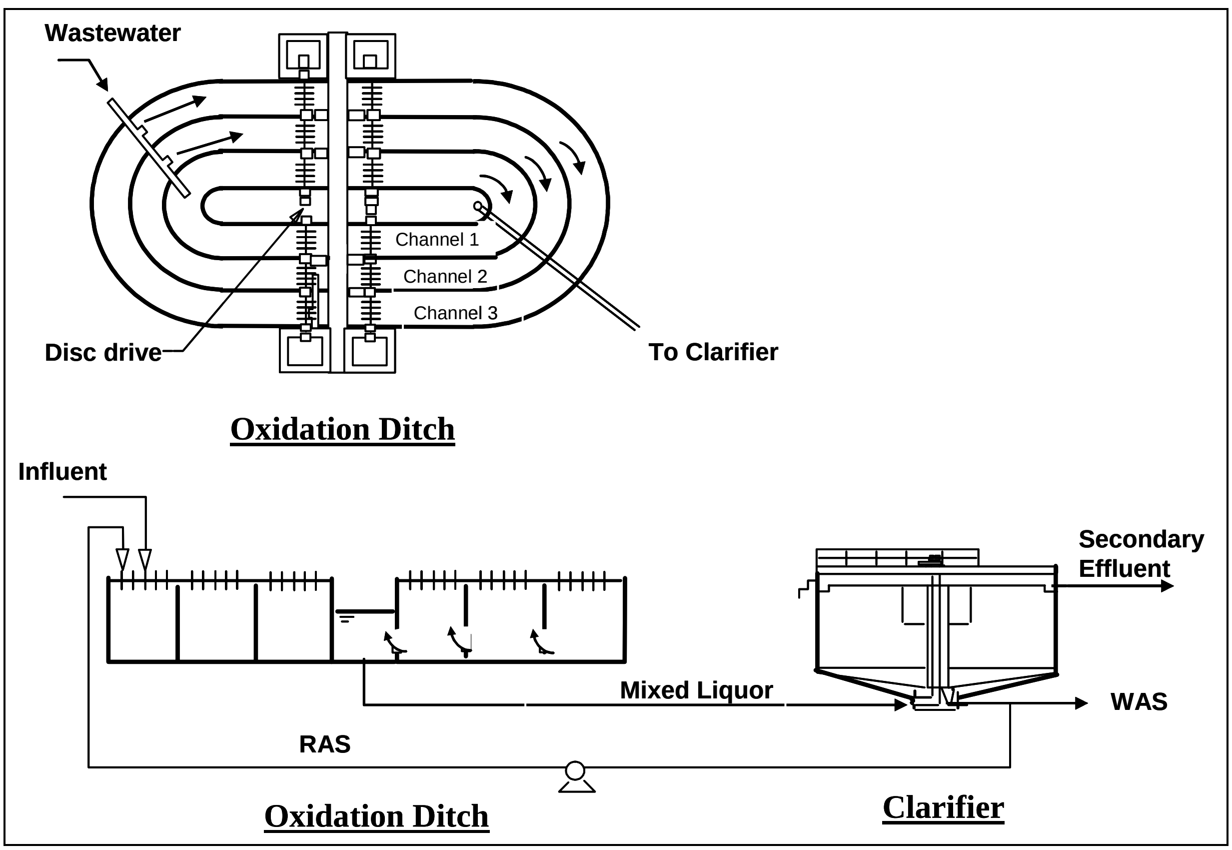
Table 1. Unit Processes at the UC Davis WWTP

Process	Description
Headworks	2 Channel Monsters® and 1 Auger Monster™
Oxidation Ditch	3 channels (Orbal by U.S. Filter/Envirex Inc.)
Clarifiers	2 clarifiers
Filters	3 filters (Hydro-Clear®)
UV Disinfection	2 channels (Trojan 3000)
Solids Storage Basins	2 basins
Solids Drying Beds	2 beds

THE CHALLENGES OF MANUAL AERATION CONTROL

The UC Davis WWTP has a three-channel U.S. Filter Envirex Orbal oxidation ditch. The design hydraulic detention time is 20.7 hours with a 20-day sludge age. Mixed liquor (MLSS) is maintained at 2,500 mg/L and 3,200 mg/L for returned activated sludge (RAS). The Orbal ditch is a single-sludge activated process with a series of three concentric looped reactors. Wastewater passes through the channels from the outermost channel, to the middle channel, and on to the innermost channel. Flow circulates around each of the three channels, allowing the raw sewage to be quickly dispersed with microorganism flocs. Figure 1 shows the ditch configuration.

Figure 1—Oxidation Ditch Configuration



Aeration (oxygen transfer) in the Orbal system is provided by 4.5-foot-diameter plastic aeration disks. These discs also provide mixed liquor recirculation within each channel to keep settleable solids in suspension. Water depth in the ditch is controlled by adjusting overflow weir height, which then changes the immersion of the disks. The amount of oxygen delivered is a function of immersion and disc speed. Power consumption increases with increased disk immersion and disc speed.

The outer channel has 50 percent of the total aeration basin volume and receives raw wastewater and RAS. The outer channel is operated at near-zero DO to create an anoxic condition where denitrification occurs. To ensure an anoxic condition is maintained in the outer channel, a minimum number of aerators must be operated to keep the oxygen supply at about 50% of the oxygen demand.

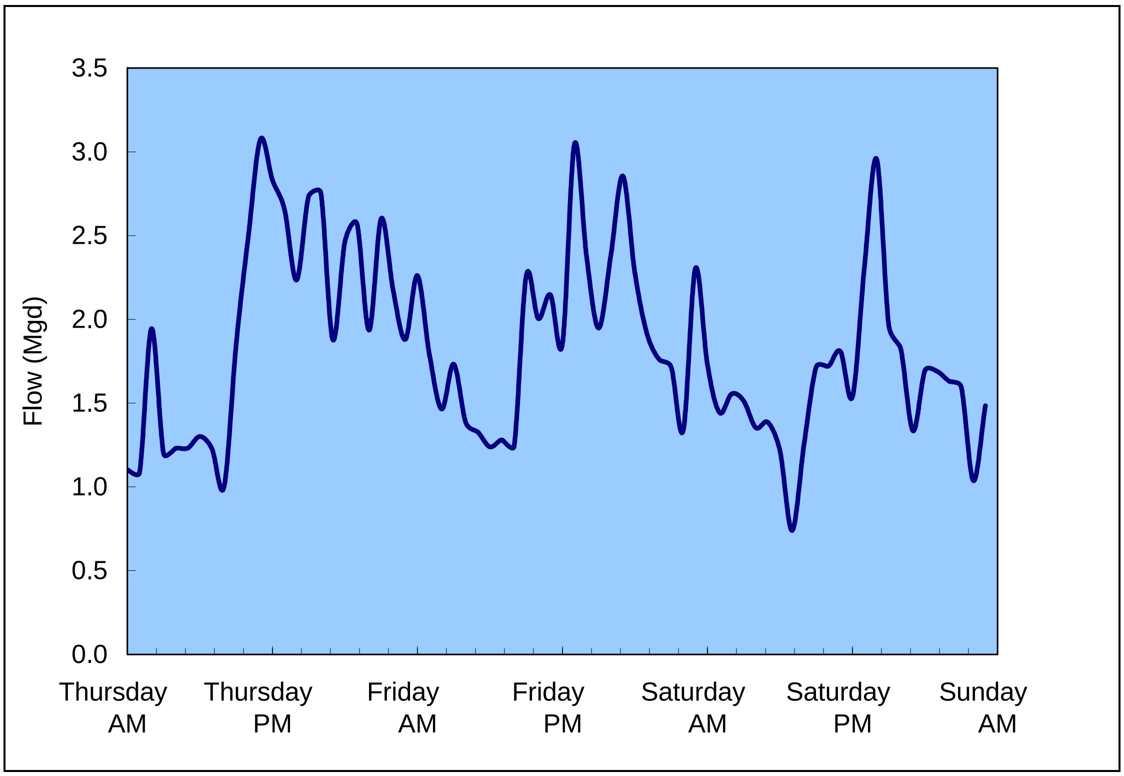
The ditch contains eight aerators: four with 40-hp motors and four with 25-hp motors. Each aerator is reversible, and capable of two speeds. There are a total of 264 discs mounted on the aerator shafts; 100 discs are installed in the outer channel, 96 discs in the middle channel, and 68 discs in the innermost channel. Discs in the innermost channel and the middle channel share a common shaft, connected by a mechanical coupler located between the two channels. The discs are designed with raised nodules shaped such that when rotated in a "Base Forward" direction they entrain a greater amount of air to the mixed liquor than when rotated in the opposite direction, "Apex Forward." Rotation in the Base Forward position requires an increase in power draw and cause a corresponding increase in oxygen delivery. Performance characteristics of the discs in a typical Orbal channel with a velocity of 1.0 foot per second (fps) are shown in Table 2.

Table 2—Disc Oxygen Transfer and Power Consumption (per disc)

	Base Forward		**Apex Forward**	
	LBS. O_2/HOUR	**BHP**	**LBS. O_2/HOUR**	**BHP**
43 RPM				
21" immersion	1.66	0.48	1.25	0.36
19" immersion	1.54	0.44	1.14	0.33
17" immersion	1.38	0.4	1.04	0.30
15" immersion	1.25	0.36	0.94	0.27
13" immersion	1.11	0.32	0.84	0.24
11" immersion	0.98	0.28	0.74	0.21
9" immersion	0.85	0.24	0.64	0.18
55 RPM				
21" immersion	2.5	0.83	1.85	0.58
19" immersion	2.28	0.73	1.68	0.53
17" immersion	2.08	0.69	1.54	0.48
15" immersion	1.88	0.62	1.39	0.44
13" immersion	1.66	0.56	1.24	0.39
11" immersion	1.48	0.49	1.09	0.34
9" immersion	1.23	0.42	0.94	0.3

As originally designed and installed, aeration control in the oxidation ditch consisted of bringing aerators on and off line, setting aerator speeds either high or low, and adjusting the height of the effluent weirs. This system offers infinite flexibility to establish a given aeration rate within the required operational ranges; however, all control functions were to be executed manually by plant operations staff. In theory, an operator could make adjustments in aerator speed, rotation direction and weir height in an attempt to match the variation in flow, BOD, and ammonia. In practice, though, disc speed and rotation provided the primary means of control since these changes could be quickly made in comparison to changing immersion. Shortly after startup in 2000, it became clear that aeration with only two speed and two rotation directions was insufficient to closely respond to changes in diurnal flow and influent characteristics. Figure 2 shows the flow variation in a typical week for the plant. The flow starts to increase at 8:00 AM and tails off at around 1:00 AM the next day, with an average flow for that period of 2.5 Mgd. From 1:00 AM to 8:00 AM the average flow is only1.2 Mgd. The wastewater strength drops from a BOD_5 of 170 mg/L during the high flow period to 80 mg/L during the low flow period.

Figure 2—Typical hourly flows at UC Davis WWTP



Theoretical oxygen demand can be calculated given flow and wastewater strength. The oxygen demand varies throughout the day in response to variations in flow and wastewater strength. The calculations below illustrate the difficulty of manually adjusting aeration to match variable oxygen demands.

1) Under the typical high flow time period, the influent BOD_5 concentration is 170 mg/L and ammonia concentration is 15 mg/L, thus:

$$Pounds\ of\ BOD_5\ loading\ per\ hour =$$

$$\frac{2.5\ Mgd \times 170\ mg/L \times 8.34\ (l/Mg)(lb/mg)}{24\,hrs} = 148\ lbs/hr$$

$$Pounds\ of\ NH_3\ loading\ per\ hour =$$

$$\frac{2.5\,Mgd \times 15\,mg/L \times 8.34\,(l/Mg)(lb/mg)}{24\,hrs} = 13.0\,lbs/hr$$

$$Pounds\ of\ total\ O_2\ demand\ per\ hour =$$

$$148 lbs\ BOD_5/hr \times 1.2\ O_2 lbs/lbBOD_5 + 13.0 lbsNH_3/hr \times 4.6\ O_2/lbsNH_3$$

$$= 237\ lbs\ O_2/hr$$

2) Under the typical low flow period, the BOD_5 concentration is 80 mg/L and ammonia concentration is 5 mg/L, thus:

$$Pounds\ of\ BOD_5\ loading\ per\ hour =$$

$$\frac{1.2\ Mgd \times 80\ mg/L \times 8.34\ (l/Mg)(lb/mg)}{24hrs} = 33.4\ lbs/hr$$

$$Pounds\ of\ NH_3\ loading\ per\ hour =$$

$$\frac{1.2\ Mgd \times 5\ mg/L \times 8.34\ (l/Mg)(lb/mg)}{24hrs} = 2.09\ lbs/hr$$

$$Pounds\ of\ total\ O_2\ demand\ per\ hour =$$

$$33.4\ lbs\ BOD_5/hr \times 1.2\ O_2 lbs/lbBOD_5 + 2.09\ lbsNH_3/hr \times 4.6\ O_2/lbsNH_3$$

$$= 49.7\ lbs\ O_2/hr$$

Data from the manufacturer can be used to calculate the amount of oxygen supplied at the selected aeration settings. For example, when the disc immersion at 15” at 55 RPM, in Apex Forward direction, the total supplied oxygen is calculated as follows:

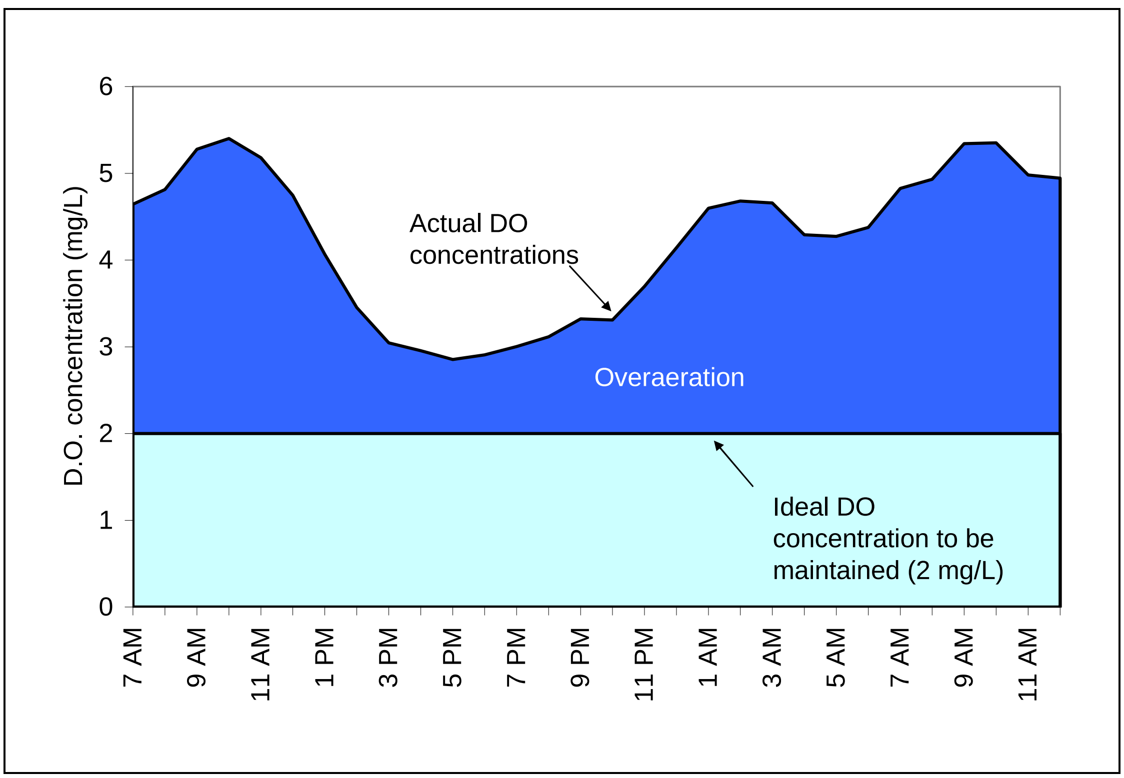
$$264\ Discs \times 1.39\ O_2 lbs/hr \times 0.8(site\_factor) = 294\ lbs/hr$$

Thus, when the aeration system is operated in this mode during the high flow period, the total amount of oxygen supplied is 294 lbs O_2/hr, which is close to the calculated oxygen demand of 237 lbs O_2/hr. However, the oxygen required for the low flow time period is 49.7 lbs O_2/hr, which is about one fifth the amount supplied by the aeration discs at their high flow settings.

Plant staff explored manually switching some drives to low speed during the night, but found it was difficult to consistently match oxygen supply with demand since flow and wastewater strength are constantly changing. Moreover, if too little oxygen is supplied, untreated wastewater could pass through the system and possibly result in permit violations. Thus, plant operators typically erred on the side of providing too much oxygen, and the ditch was often found to be in an over-aerated state. This practice wastes energy and makes for unstable biological conditions. Research literature discusses the disadvantage of over-aerated mixed liquor, which forms pin flocs at the sedimentation basin. Pin flocs remain in suspension and reduce the effluent quality after secondary treatment.

U.S. Filter/Envirex Inc. suggests the ditch channel oxygen to be operated in a “0-1-2” mode, which maintains the oxygen level at approximately 0 mg/L for the outer channel, 1 mg/L for the middle channel and 2 mg/L for the innermost channel. This mode of the operation is designed to ensure the ditch achieves proper BOD, ammonia, and nitrate removal. At a constant aeration rate, dissolved oxygen in the outer channel was found to be relatively stable, typically varying from 0.4 mg/L to 0.8 mg/L with an average of 0.5 mg/L. In contrast, the innermost channel experienced a wide swing in DO throughout the day. Figure 3 illustrates typical weekday DO levels in the innermost channel during manual aeration. The oxygen level in the innermost channel increased from 3.0 mg/L at 9 PM to 5.4 mg/L at 10 AM next day. The daily fluctuations in DO levels were even larger during the weekend when campus wastewater flows were lower.

Figure 3—DO Levels in the Innermost Oxidation Ditch Channel under Manual Aeration



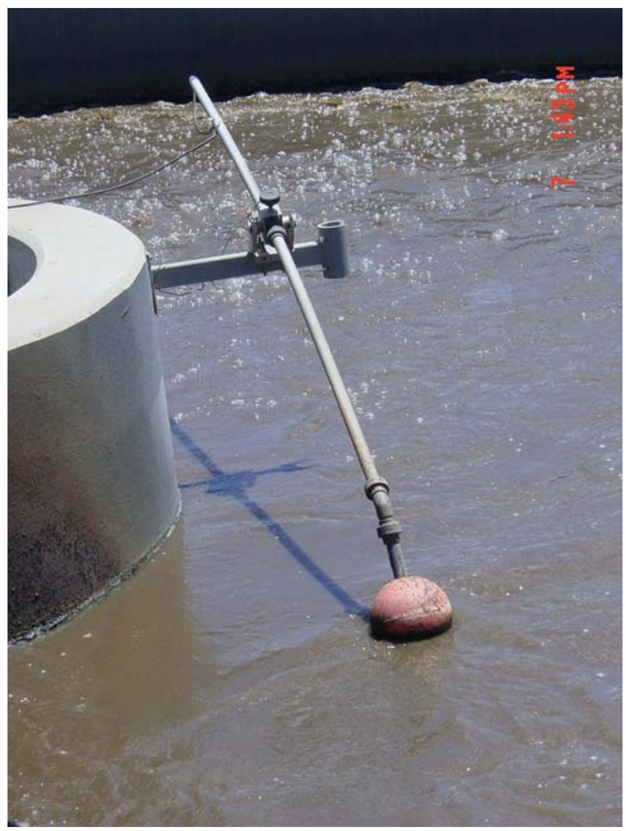
CONVERSION TO AUTOMATIC AERATION CONTROL

Several physical and process control changes were implemented to keep aeration in line with biological demand. First, to control the amount of oxygen supplied by the aerators, variable-frequency drives (VFDs) were installed on two of the aerator motors. Second, a continuous on-line DO monitor was installed in the innermost channel. The existing SCADA system was then programmed to modify the speed of the aerators in response to actual DO levels. Installation details for these components are provided below.

On-line Continuous DO Monitoring

Traditional on-line DO monitoring devices are not well suited for continuous use in the activated sludge process. Operation and maintenance problems are especially severe for biological processes like UC Davis' which employ a long Mean Cell Retention Time (MCRT) without primary clarifiers. In these applications, debris (e.g., plastic and rags) quickly tangle around traditional DO sensors, causing inaccurate readings. Plant operators often find excessive maintenance and calibration are required to keep the DO meters in service. In response to these problems, a new debris-free type of DO monitoring device, as shown in Figure 4, was selected for the DO loop control at UC Davis. The device consists of a float ball with a DO sensor mounted near the bottom of the ball. Half of the float ball is immersed under water. Because of its smooth surface, no debris can grab on the sensor, and so debris does not affect the accuracy of the DO readings.

Figure 4—Cerlic® Float Ball DO Monitor



The Cerlic® float-ball DO monitoring device was mounted on the ditch inner wall along with the enclosed probe analyzer box, which is powered by an uninterrupted power supply (UPS). The UPS was powered by an existing 120-volt AC outlet. The DO analyzer was connected to the SCADA in the plant administration building via an existing conduit. Plant staff calibrate the meter on a monthly basis. To verify proper operation, plant staff record DO levels in the channel each day using a portable DO meter and compare these results to the on-line data.

VFD Installation

Two Danfoss VLT®8000 Variable Frequency Drives (VFD) were installed to replace the existing 2-speed motors. The other two aerators on the innermost channel were set to run continuously at a constant low speed to satisfy the minimum oxygen demand during low loading time periods. The SCADA system was modified to communicate with the two VFDs to throttle the speed of the aerators to maintain a DO setpoint of 2.0 mg/L. Delays were programmed into the control logic to provide smooth transitions and avoid excessive cycling.

Under DO control, the PLC controls the process by sending an output to the VFDs, and the VFDs then regulate the motor speeds accordingly. The greater the error between a pre-set DO value and the DO from the ditch on-line DO meter, the faster the disc drive runs, and vice versa. This control strategy allows the amount of oxygen delivered by the aeration system to match the oxygen demand and thus eliminate over-aeration, with a resultant power reduction.

These modifications were started in late November 2003 and were completed at the end of December 2004. The total cost for design, construction, and startup was approximately $64,000. This estimate includes all labor provided by the UC Davis WWTP staff, even though these costs reflect a redirection of internal resources rather than additional expenses.

RESULTS

Results for the first 12 months of operations (January-December 2004) are described below.

Energy Use

Shortly after start-up, we installed power monitors on the two modified aerator motors to compare the original design with the revised design. In the first phase of this test, the two VFDs were set to run in a 2-speed mode just as they were manually operated before the VFDs were installed. In the second phase of the test, the VFDs were set to run automatically under DO loop control during similar flow conditions. In each case, power draw was recorded using data loggers at five minutes intervals. As shown in Figure 5, power consumption after installing the VFDs varies closely in response to the flow pattern while only minor changes were possible via 2-speed motor control.

There was a clear reduction in power consumption following implementation of the process control changes. Total power consumption for the WWTP was reduced by an average of 6%. This reduction in energy use occurred while flows to the WWTP increased by an average of nearly 20%. Figure 6 shows total WWTP energy use per million gallon of effluent treated to account for the increase in flow over the study period.

During the first year of operation, the use of VFDs for oxidation ditch aeration in conjunction with DO feedback-loop control reduced total WWTP electrical consumption by an average of 23% or 755 kilowatt-hours per million gallons (kWh/Mg).

Figure 5—Typical Electrical Use Before and After Process Control Changes

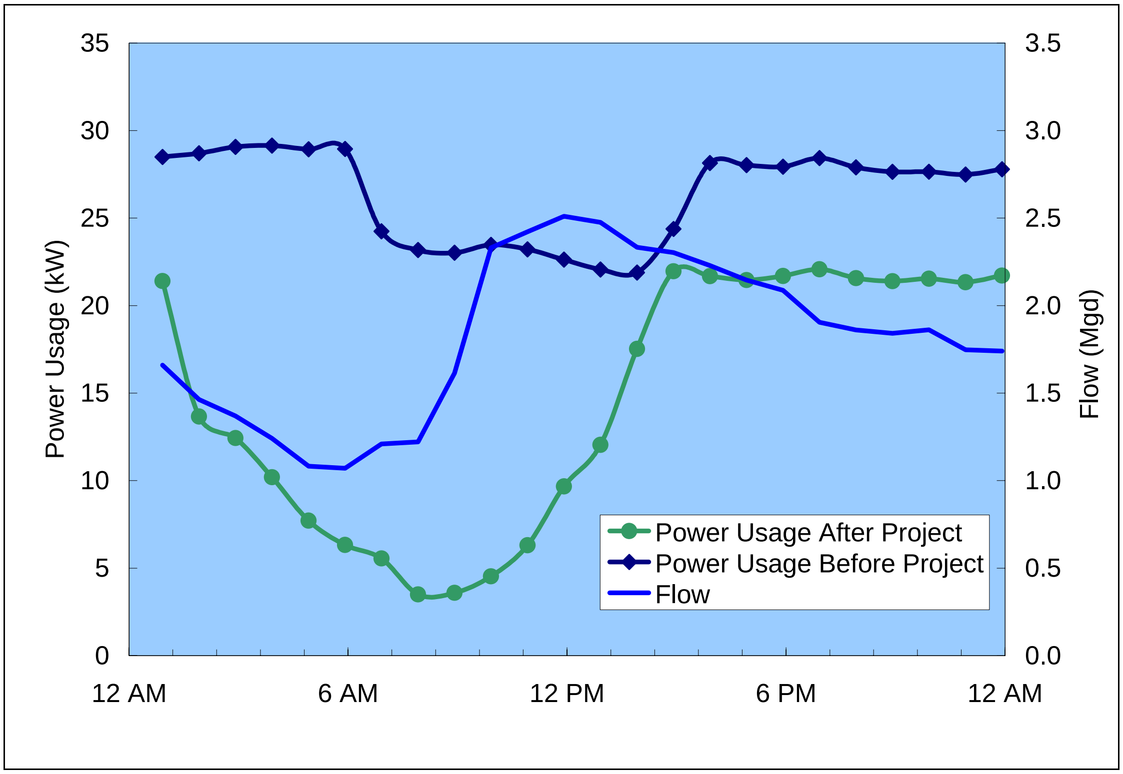
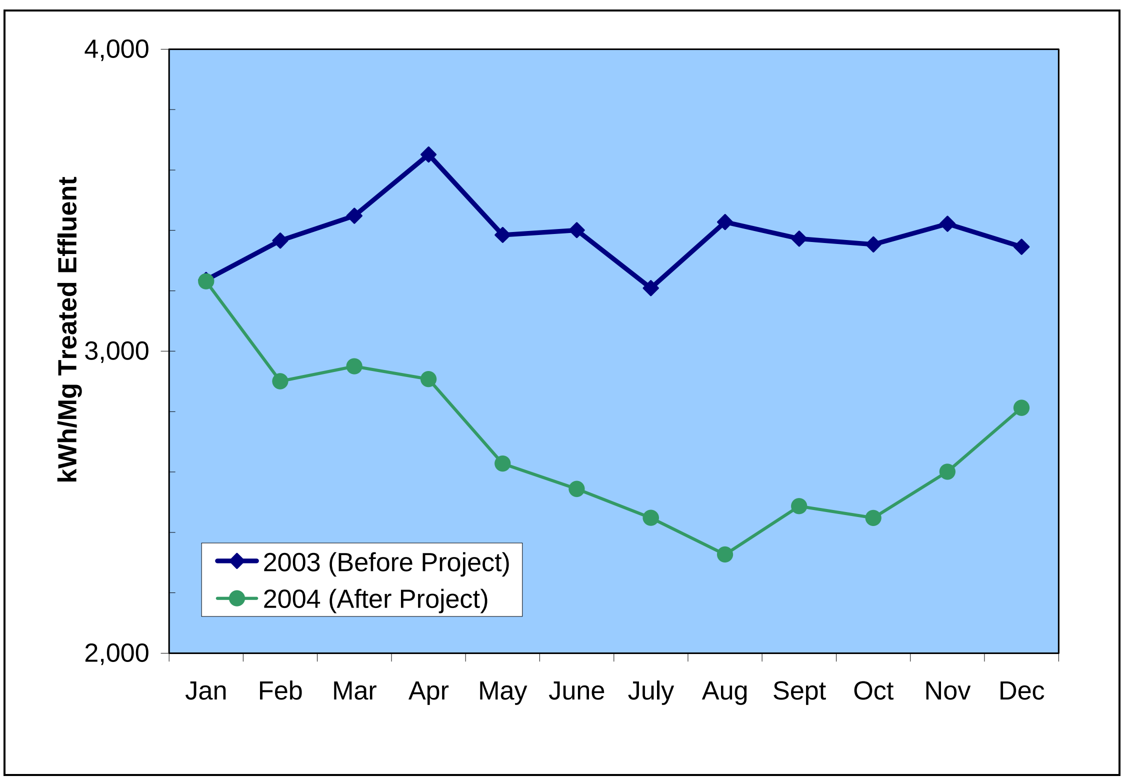
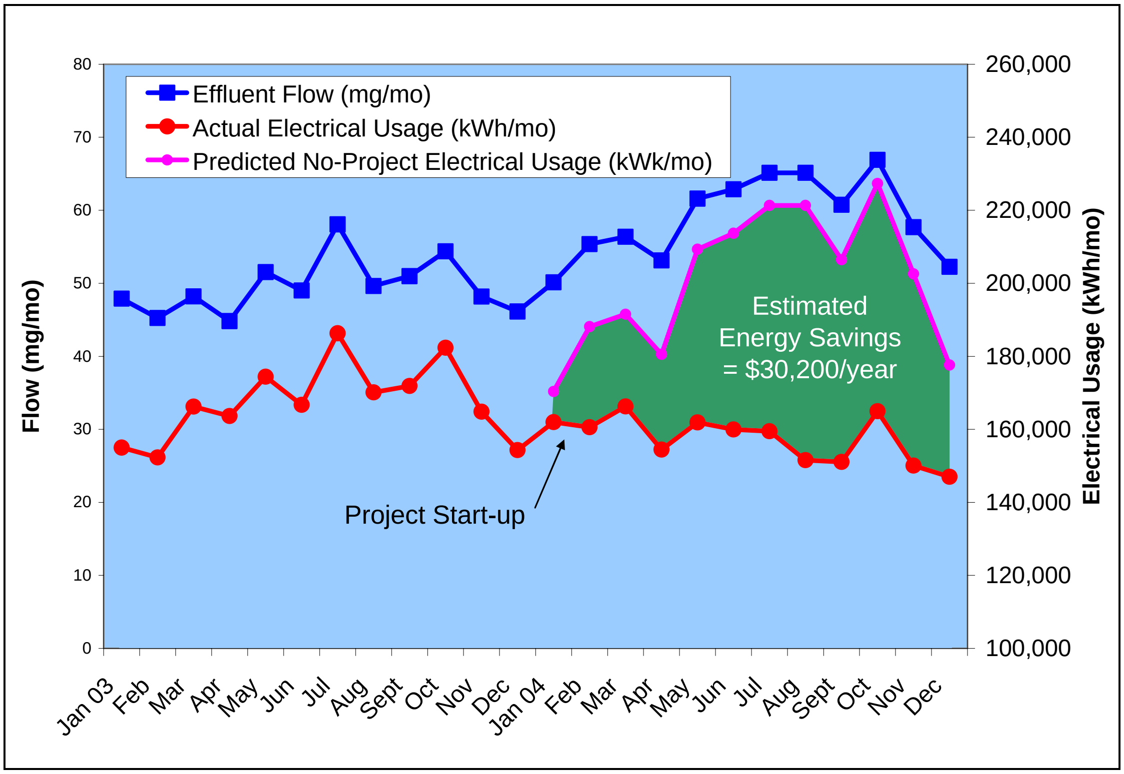


Figure 6—Flow-adjusted WWTP Electrical Use



UC Davis buys electricity for the relatively low rate of $0.054/kWh, but the project nonetheless resulted in a noticeable decrease in WWTP operating costs. While the campus was experiencing a period of significant growth, energy use by the WWTP actually decreased. Had the project not been implemented, energy use was projected to have increased significantly. Figure 7 shows projected and actual energy use for the WWTP. We estimate that the project saved the University approximately $30,200 during the first year of operation. This savings represents approximately 3% of the total annual operation and maintenance budget for the WWTP.

Figure 7—Estimated Project Energy Savings



Water Quality

Tables 3 and 4 summarize key water quality parameters before and after the design changes were made. The WWTP continued to produce high-quality effluent, meeting all permit conditions in the months following implementation of the project. The SVI (Sludge Volume Index) showed some slight change. The SVI is an indicator of sludge quality and should be maintained in the range of 100 to 180. Before the process control changes were made, the WWTP typically operated below this range. The SVI went from an average of 84 in 2003 to 99 in 2004. This change reflects a modest improvement in treatment.

Table 3—Secondary Treatment Water Quality (Prior to Filtration)

Month	2003				2004			
	TSS	Turbidity	SVI	pH	TSS	Turbidity	SVI	pH
January	8.6	2.24	60	7.62	8.0	2.55	93	7.87
February	7.0	1.95	71	7.62	11.9	3.52	112	7.55
March	7.0	2.2	68	7.68	5.2	1.56	99	7.65
April	4.8	1.71	83	7.60	4.7	1.45	162	7.62
May	5.2	1.73	85	7.99	5.3	0.33	115	7.95
June	5.8	1.97	82	7.92	8.9	2.88	106	8.04
July	5.3	1.93	76	7.96	7.3	2.24	67	8.08
August	6.5	2.04	83	7.92	11.0	2.97	67	8.00
September	8.4	2.41	75	7.97	8.6	2.64	98	8.02
October	10.4	1.87	112	7.95	8.2	1.89	89	8.05
November	7.4	2.38	111	7.98	6.0	1.69	85	7.97
December	8.19	2.53	104	8.06	6.5	2.05	89	7.96
Average	**7.05**	**2.08**	**84**	**7.86**	**7.64**	**2.15**	**99**	**7.90**

Table 4—Effluent Water Quality after Tertiary Treatment

Month	2003				2004			
	TSS	Turbidity	BOD_5	NH_3-N	TSS	Turbidity	BOD_5	NH_3-N
January	0.92	1.58	1.72	<0.5	0.64	0.33	1.27	<0.5
February	0.51	0.59	1.18	<0.5	2.20	1.97	1.66	<0.5
March	1.00	0.91	1.65	<0.5	0.40	0.45	1.31	<0.5
April	1.20	1.38	1.44	0.87	0.19	0.46	0.57	<0.5
May	0.92	0.93	1.25	<0.5	0.25	0.33	1.34	<0.5
June	1.04	0.52	1.17	<0.5	0.91	0.91	2.00	<0.5
July	0.54	0.40	1.35	<0.5	0.47	0.45	1.28	<0.5
August	0.66	0.47	1.57	<0.5	0.37	0.45	1.19	<0.5
September	0.65	0.64	1.85	<0.5	0.27	0.53	0.95	<0.5
October	0.40	0.35	1.80	<0.5	0.30	0.52	1.63	<0.5
November	0.32	0.37	1.19	<0.5	0.40	0.74	2.50	<0.5
December	0.59	0.48	1.10	<0.5	1.00	0.74	1.96	<0.5
Average	**0.73**	**1.12**	**1.44**	**0.87**	**0.62**	**0.80**	**1.47**	**<0.5**

The data collected thus far suggest that final effluent water quality has, on average, slightly improved after installing the VFDs. Ammonia as nitrogen remained below 0.5 mg/L in 2004 while removal varied in 2003. This was expected since the DO loop control provides instantaneous adjustment to match the in-coming oxygen demand. Under manual control, aeration could only be set based on an average load. Thus, if there were a sudden increase in the influent ammonia concentrations, some ammonia would bleed through the oxidation ditch. Beyond these metrics, the WWTP operators strongly prefer the new process control system, as it provides an extremely stable biological treatment process.

CONCLUSIONS

The process control changes necessary to automate oxidation ditch aeration at the UC Davis WWTP were relatively easy to implement and our data indicates that the project has significantly reduced energy use while maintaining or improving effluent water quality. After twelve months of operation, our principal conclusions are as follows:

- The availability of a debris-free, low-maintenance, in-line DO meter is an important innovation that makes automatic DO loop control operationally practical for activated sludge treatment systems. The tested DO monitoring system has proven to be extremely reliable with very little maintenance required. The automated control system has consistently maintained set-point DO levels in the oxidation ditch without discernable drift or error.

- The use of VFDs for oxidation ditch aeration in conjunction with DO feedback-loop control has reduced WWTP electrical consumption by an average of 23% or 755 kilowatt-hours per million gallons (kWh/Mg) (Figure 6). The project was found to have a 1.2 year payback at the prevailing municipal electrical rate of $0.09/kWh.

- Beyond energy efficiency, the ability to maintain DO at prescribed levels in the oxidation ditch has afforded operators a higher degree of biological process control. Effluent quality has improved as a result. The sludge volume index (SVI) increased from an average of 84 to 99. Ammonia as nitrogen has consistently remained below 0.5 mg/L after implementation.

- The revised system was designed to consistently maintain DO at fixed levels with the goal of maintaining a stable biological treatment process. However, other control strategies that vary DO levels over time are also possible. Use of variable DO control strategies might allow for a further reduction in energy consumption or enhanced biological treatment. These concepts are recommended for future study.

Given these positive results, operators of existing activated sludge WWTPs with manual aeration and designers of new WWTPs should consider implementing similar process control strategies.

ACKNOWLEDGEMENTS

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